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Comparative Study and Simulation of Mid-range Wireless Power Transfer at Various Transmission Distance

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Comparative Study and Simulation of Mid-range Wireless Power Transfer at Various Transmission Distance

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Abstract. Wireless power transfer would be the niche of research in next decade which is significant to reduce the cable and charges consumption for electronic devices. This paper presents the simulation result of electric and magnetic wave behaviour in mid-range wireless power transfer and various transmission distance in the range of 8 – 16 cm. Simulation result using CST microwave studio shows that scattering parameter in the power transmission decreases from 0.6509 down to 0.5137 with the increase in distance. The transmitted electric field at the receiver decreases from 1615 V/m to 1086 V/m whereas the magnetic field decreases from 32.63 A/m down to 24.85 A/m. Results show that 4-coils magnetic resonance coupling is an ideal approach for mid-range wireless power transfer.

1. Introduction

Fundamental of wireless power transfer (WPT) was firstly introduced back in the 1800s [1]. Today, WPT is gaining strong attention due to its functionality in transmitting power and energy over distance using air as the transmission medium [2]. Such approach is to sustain a greener environment which is free from chargers, cables and transmission wire. The operational WPT occurs in range of millimetres (short range WPT), range of centimetres (mid-range WPT) and range of meters to kilometres (long range WPT). There are numerous research of short range WPT since the past decade, and the operation of long range WPT using radio-frequency or microwave has been ambiguous towards human health impact [3, 4].

In such scenario, mid-range WPT has recently drawn researchers' attention to achieve a high transmission efficiency at a desired transmission distance [5, 6]. Mid-range WPT received great achievement in 2014 when Korea Advanced Institute of Science and Technology (KAIST) produced a 209 W of power to charge 40 smartphones in the 20 kHz of operating frequency [7]. The major drawback of the finding is that the set-up is bulky and immobile. *Song et al.* has recently discovered a dielectric resonator to enhance the performance of mid-range WPT [8]. Tang *et al.* has presented an improved mid-range WPT using segmented coil transformer which made applicable in implantable heart pumps [9]. The improvement in the stability of mid-range WPT was justified by *Lee et al.* using the implementation of relay resonator [10].

Several methods have been proposed to achieve mid-range wireless power transfer namely: 2-coils, 3-coils and 4-coils magnetic resonance coupling [11, 12]. Previous research justified that 4-coils magnetic resonance coupling would be the promising method solely because it functions based on impedance matching which hence optimized the power and energy level received by the load [13]. In

2017, Yang has recently proved that 4-coils magnetic resonance is able to extend the power transmission distance as compared to the 2-coils system [14]. This is because 4-coils system will have a stronger magnetic coupling between the source and load coils.

This paper performs simulation work to observe the coupling between the 4-coils system as well as to study the change in coupling and power transmittance achievable at the load coil when the distance between the source and load coil varies. Section 2 presents the ideal circuitry of transmitter unit and receiver unit for mid-range wireless power transfer which adopts the 4-coils magnetic resonance coupling method and some fundamental equations for the magnetic coupled resonator. The simulation result of wireless power transfer is presented in section 3 using CST microwave studio at various transmission distance in the range of 8-16 cm. Comparative study of the scattering (*S*) parameter, impedance (*Z*) parameter, electric (*E*) and magnetic (*H*) field behavior are presented and discussed.

2. Mid-range Wireless Power Transfer System Design

Figure 1 shows the ideal circuitry structure for a mid-range wireless power transfer. In the transmitter unit, the rectifier will first convert the input AC wave to DC signal. Then the DC signal will be converted to a high AC output via the oscillator. Power amplifier is recommended to amplify the signal before power transmission at the coils. The 4-coils magnetic resonance coupling system comprises of the source coil, transmitter (Tx) coil, receiver (Rx) coil, and the load coil [15]. Resonance coupling will occur between source and transmitter, transmitter and receiver, as well as receiver and coil. Power transmittance and transfer in energy is achieved when the coils are operating at the same frequency. Then, at the receiver unit, the rectifier will convert the AC output from the load coil to a DC output. Finally, the DC output will power up the load connected at the end of receiver unit. It is crucial to ensure that appropriate current and voltage value is received at the load to power up electronic devices such as mobile phone, tablet, laptop etc.

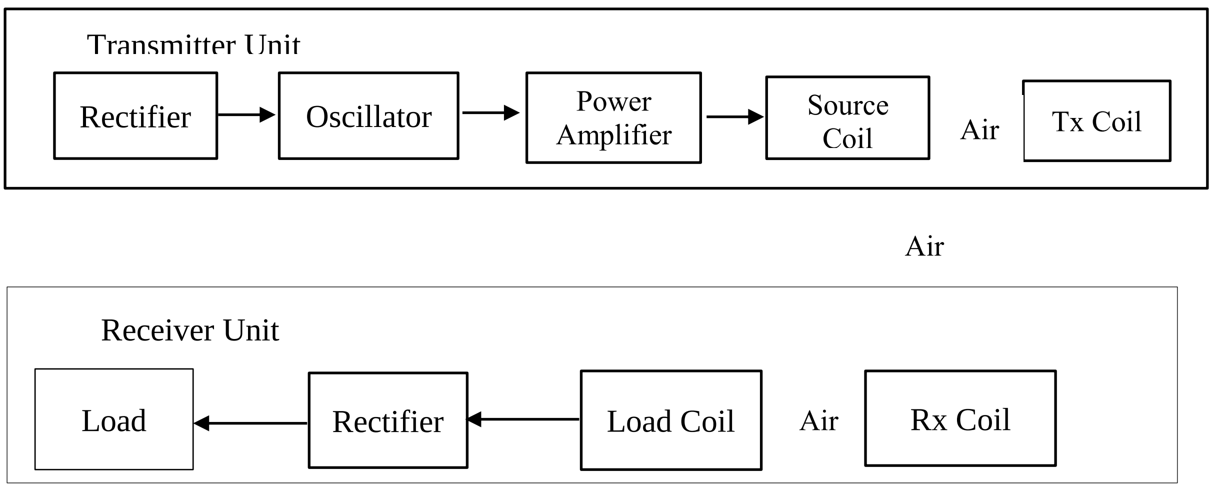

Figure 1. Transmitter and receiver units for mid-range wireless power transfer

The coil inductance, *L* is defined using Wheeler's equation [16]:

$$\boldsymbol{L} = \frac{\boldsymbol{r^2 N^2}}{\boldsymbol{2.54 \times (8r + 11b)}} \tag{1}$$

where *r* is the radius of coil, *N* is the number of turns and *b* is the depth of winding.

A high quality factor (Q) is desired in wireless power transfer to ensure a high power efficiency. The Q-factor of 4-coils system is expressed as [17]:

$$\boldsymbol{Q = \frac{1}{R}\sqrt{\frac{L}{C}}} \tag{2}$$

in which R is resistance, L is the inductance and C is the capacitance value.

The efficiency of transmittance rate which explains the rate of power transfer received from the load coil from the source coil reads as [18]:

$$\boldsymbol{\eta = \frac{P_{\text{out}}}{P_{in}} = \frac{I_4^2 R_L}{I_1^2\left(\frac{R_S}{4}\right)} = |S_{12}|^2} \tag{3}$$

where $I_1$and I_4 are current flow at source coil and load coil, respectively. In addition, R_S and R_L represent the resistance and source and load coils.

Maximum power transferred from the source coil to the load coil, $|S_{12}|_{\text{max}}$ is expressed as [15, 18]:

$$\boldsymbol{|S_{12}|_{\text{max}} = \frac{k_{12}k_{34}Q_1Q_4R_L}{k_{23}^{*}\sqrt{L_1\omega_1L_4\omega_4}}} \tag{4}$$

where Q_1 and Q_2 are quality factors at the source and load coils, ω_1 and ω_4 are the operating frequency at source and load coil, k_{12} is the magnetic resonance coupling resonance between the source and transmitter coil, k_{23} is the coupling between transmitter and receiver coil and k_{34} is coupling between the receiver and load coil. From equation 4, a strong coupling of k_{12} and k_{34} together with a low coupling of k_{23}would be ideal case to achieve maximum energy transfer.

3. Results and Discussion

This research was undertaken to perform simulation of 4-coils magnetic resonance coupling which is applicable in the mid-range wireless power transfer. Figure 2 shows the alignment of 4-coils structure which comprises of the source coil, transmitter coil, receiver coil and the load coil. A discrete port is placed at the source coil and load coil to transmit and receive signal, respectively.

Table 1 lists the variation of distance, d between source and transmitter, transmitter and receiver, as well as receiver and load coil. This variation is significant to perform comparative study of wireless power transfer at various transmitting distance.

Simulation is performed using CST microwave studio and results are presented in figure 3, 4, and 5. The electric field and magnetic field behaviours are observed when the coils are operating at a resonance frequency. For all the simulation circuitry presented in figure 3-5, the radius of source and load coils are 30 mm, whereas transmitter and receiver coils are ten turns with 50 mm of radius.

Table 1. 3 sets of separation distance between source coil and load coil

Fig	d between source and transmitter coil (cm)	d between transmitter and receiver coil (cm)	d between receiver and load coil (cm)	d between source and load coil (cm)
3	2	4	2	8
4	3	6	3	12
5	4	8	4	16

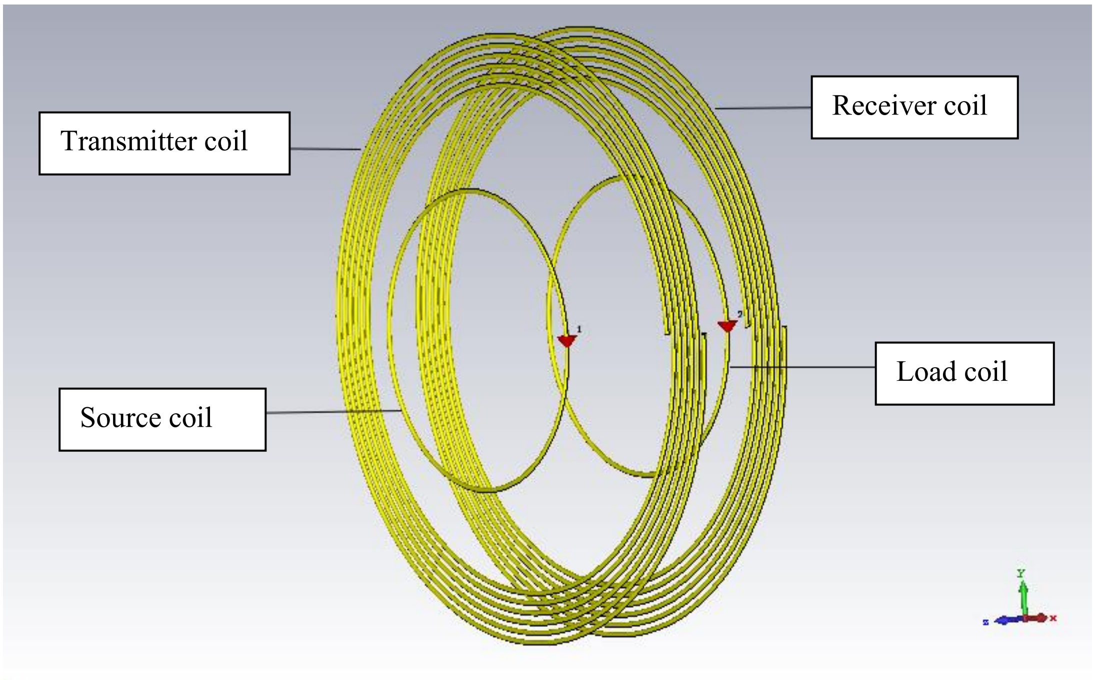

Figure 2. 4-coils system for magnetic resonance

Table 2 lists the performance parameters of 4-coils system design in figure 2 at three various distance between the source coil and load coil at 8, 12, and 16 cm of transmittance distance. The resonance frequency is identified at 17.151 MHz, 18.551 MHz and 21.485 MHz. The resonance frequency is identified at the maximum S-parameter value where the strongest coupling between the coils occurs.

Simulation result shows that the S-parameter for power transmitted from the source coil to load coil (S_{12}) as presented in equation 4 decreases from 0.6509 to 0.5137 when the distance of transmission increases from 8 cm to 16 cm. Such result reflects that the transmittance efficiency decreases from 42.36 % down to 26.38 %. In addition, table 2 presents the impedance parameters and the variation of electric field and magnetic field at the source and load coil.

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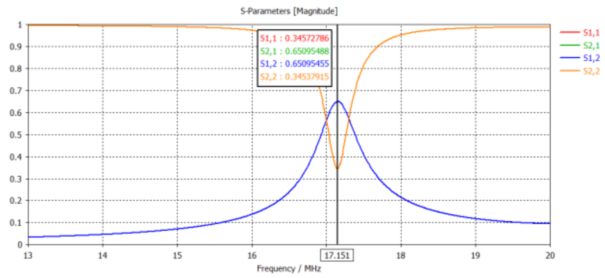
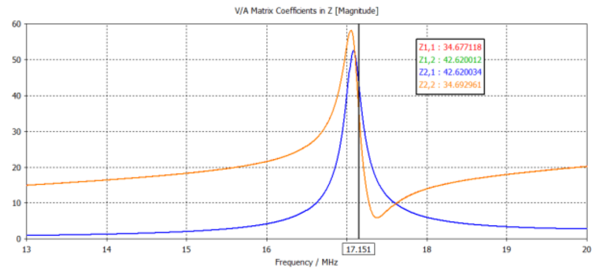
Table 2. S-parameters, Z-parameters, E-field and H-field distribution at various distance between source coil and load coil

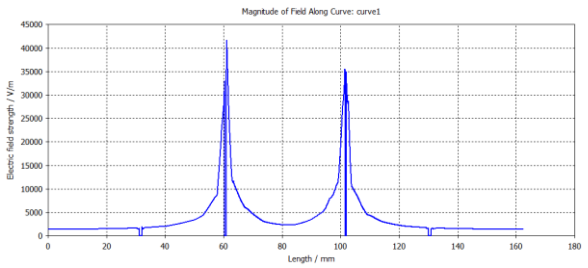
Fig	S-parameters		Z-parameters		E-field (V/m)		H-field (A/m)	
	S_{11}	S_{12}	Z_{11}	Z_{12}	Source	Load	Source	Load
3	0.3457	0.6509	34.67	42.62	1990.9	1615	54.94	32.63
4	0.4228	0.5745	27.19	32.99	1559.5	1546	55.30	31.56
5	0.4782	0.5137	28.55	28.69	1263.8	1086	53.62	24.85



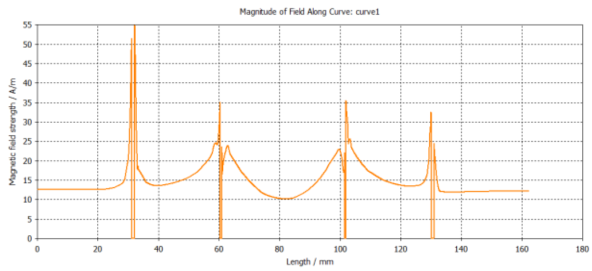
a) S-parameters



b) Z-parameters

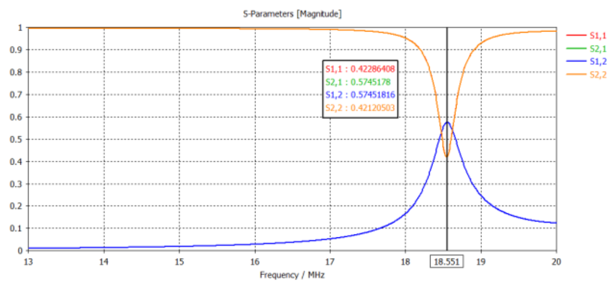


c) E-field distribution

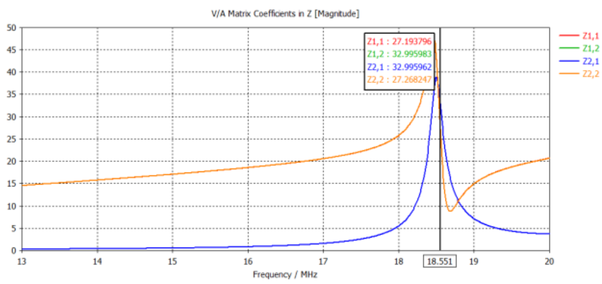


d) H-field distribution

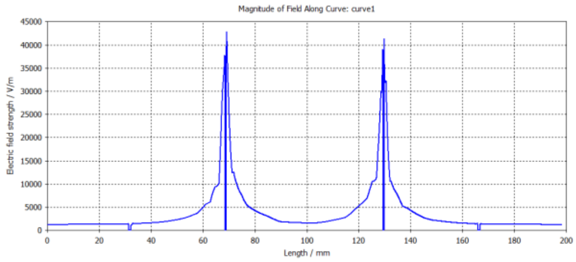
Figure 3. Output parameters for 8 cm distance between source coil and load coil



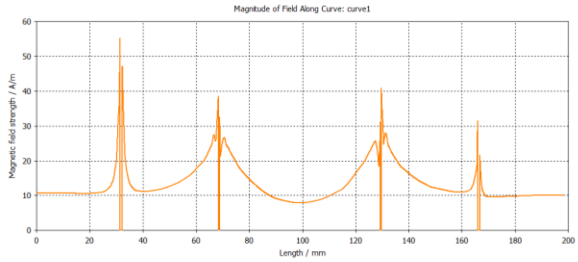
a) S-parameters



b) Z-parameters

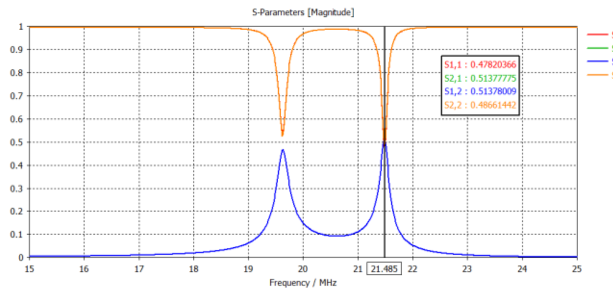


c) E-field distribution

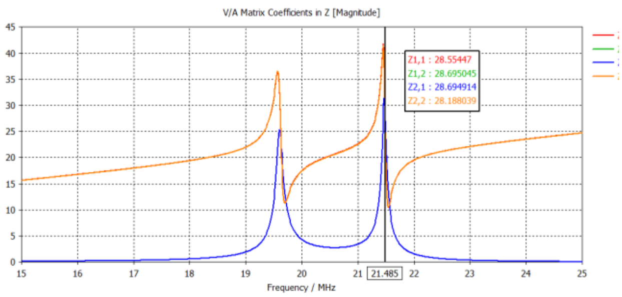


d) H-field distribution

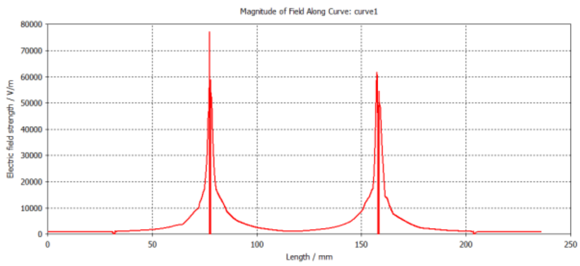
Figure 4. Output parameters for 12 cm distance between source coil and load coil



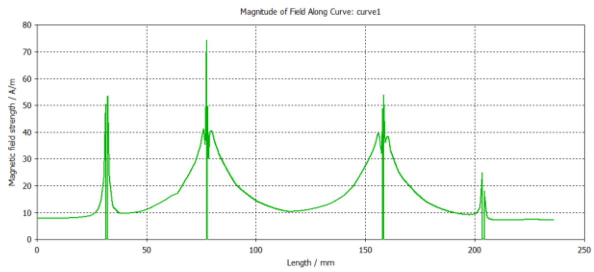
a) S-parameters



b) Z-parameters



c) E-field distribution



d) H-field distribution

Figure 5. Output parameters for 16 cm distance between source coil and load coil

4. Conclusion and Future Recommendation

This paper performs a comparative study on mid-range wireless power transfer at various transmittance distance using magnetic resonance coupling. Simulation results shows that the resonance frequency increases with respect to the transmission distance. The ratio of output power and input power drops from 0.6509 down to 0.5137 when the transmission distance increases from 8 cm to 16 cm. In addition, the impedance parameters, electric and magnetic field behavior are compared. Hence, result shows that magnetic resonance coupling is an ideal mechanism in mid-range wireless power transfer. Power transmittance could be achieved at a higher transmittance distance, given that the coils resonate in the same frequency. Other design parameters such as the ratio of distance between source coil and transmitter coil with respect to transmitter coil and receiver coil as well as number of turns or radius of the coil could be further investigated to achieve an optimum performance result in mid-range wireless power transfer.

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References

[1] Miller, J. M., Scudiere, M. B., McKeever, J. W., & White, C. (2011). Wireless power transfer. In *Oak ridge National Laboratery's Power Electronics Symposium*.

[2] Imura, T., Okabe, H., & Hori, Y. (2009, September). Basic experimental study on helical antennas of wireless power transfer for electric vehicles by using magnetic resonant couplings. In *Vehicle Power and Propulsion Conference, 2009. VPPC'09. IEEE* (pp. 936-940). IEEE.

[3] Hui, S. Y. R., Zhong, W., & Lee, C. K. (2014). A critical review of recent progress in mid-range wireless power transfer. *IEEE Transactions on Power Electronics*, *29*(9), 4500-4511.

[4] Lyu, Y. L., Meng, F. Y., Yang, G. H., Che, B. J., Wu, Q., Sun, L., & Li, J. L. W. (2015). A method of using nonidentical resonant coils for frequency splitting elimination in wireless power transfer. *IEEE Transactions on Power Electronics*, *30*(11), 6097-6107.

[5] Kurs, A., Karalis, A., Moffatt, R., Joannopoulos, J. D., Fisher, P., & Soljačić, M. (2007). Wireless power transfer via strongly coupled magnetic resonances. *science*, *317*(5834), 83-86.

[6] Zhong, W. X., & Hui, S. Y. R. (2015). Maximum energy efficiency tracking for wireless power transfer systems. *IEEE Transactions on Power Electronics*, *30*(7), 4025-4034.

[7] Yoon, U. (2017). Electrification of Other Transportation Systems. In *The On-line Electric Vehicle* (pp. 261-268). Springer International Publishing.

[8] Song, M., Belov, P. A., & Kapitanova, P. V. (2017, May). Dielectric resonators for mid-range wireless power transfer application. In *Wireless Power Transfer Conference (WPTC), 2017 IEEE* (pp. 1-3). IEEE.

[9] Tang, S. C., Lun, T. L. T., Guo, Z., Kwok, K. W., & McDannold, N. J. (2017). Intermediate Range Wireless Power Transfer with Segmented Coil Transmitters for Implantable Heart Pumps. *IEEE Transactions on Power Electronics*, *32*(5), 3844-3857.

[10] Lee, J., Lee, K., & Cho, D. H. (2017). Stability Improvement of Transmission Efficiency Based on a Relay Resonator in a Wireless Power Transfer System. *IEEE Transactions on Power Electronics*, *32*(5), 3297-3300.

[11] Zhong, W. X., Zhang, C., Liu, X., & Hui, S. R. (2015). A methodology for making a three-coil wireless power transfer system more energy efficient than a two-coil counterpart for extended transfer distance. *IEEE Transactions on Power Electronics*, *30*(2), 933-942.

[12] Huang, R., & Zhang, B. (2015). Frequency, impedance characteristics and HF converters of two-coil and four-coil wireless power transfer. *IEEE Journal of Emerging and selected topics in Power Electronics*, *3*(1), 177-183.

[13] Kiani, M., & Ghovanloo, M. (2012). The circuit theory behind coupled-mode magnetic resonance-based wireless power transmission. *IEEE Transactions on Circuits and Systems I: Regular Papers*, *59*(9), 2065-2074.

[14] Yang, D., Won, S., & Hong, H. (2017, May). Design of Range Adaptive Wireless Power Transfer System Using Non-coaxial Coils. In *IOP Conference Series: Materials Science and Engineering* (Vol. 199, No. 1, p. 012008). IOP Publishing.

[15] Duong, T. P., & Lee, J. W. (2015). A dynamically adaptable impedance-matching system for midrange wireless power transfer with misalignment. *Energies*, *8*(8), 7593-7617.

[16] Wheeler, H. A. (1958). The spherical coil as an inductor, shield, or antenna. *Proceedings of the IRE*, *46*(9), 1595-1602.

[17] Barman, S. D., Reza, A. W., Kumar, N., & Anowar, T. I. (2016). Two-side Impedance Matching for Maximum Wireless Power Transmission. *IETE Journal of Research*, *62*(4), 532-539.

[18] Cross, V. R., Hester, R. K., & Waugh, J. S. (1976). Single coil probe with transmission-line tuning for nuclear magnetic double resonance. *Review of Scientific Instruments*, *47*(12), 1486-1488.